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by V. N. Konashenok

from "Novoye o Venere i Marse"
by V. N. Konashenok and K. Ya. Kondrat'yev
"Gidrometeorologicheskoye" Press, Leningrad, 1970

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CONTEMPORARY IDEAS ABOUT THE ATMOSPHERE OF VENUS

V. N. Konashenok

ABSTRACT. The methods and the results of the Venus atmospheric research with the help of spacecrafts, Venus-4, Venus-5, Venus-6 and Mariner-5 are described and chief results of recent ground observations are given. Various experimental results are compared and analyzed from the point of view of the presence of the discrepancies. Then the principal problems associated with the theoretical interpretation of the given observations, as well as with the modeling of the upper and lower atmosphere are dealt with.

October 1967 went down as a significant month in the history of investigations of Venus. On October 18, the Soviet automatic spacecraft Venera-4 completed a smooth descent in Venus' atmosphere and transmitted to Earth the first direct data on the pressure, temperature, density, and composition of the atmosphere at various altitudes. On the following day the American interplanetary spacecraft Mariner-5 flew past Venus, providing supplementary information about the constituents of Venus' atmosphere. These interplanetary flights gave a powerful impetus to the carrying out of a wide series of experimental and theoretical investigations, as a result of which our ideas about Venus were significantly broadened. The number of scientific publications devoted to the problems of this planet underwent an extraordinary growth in recent times. The present information is intended to elucidate the fundamental results of the papers published in 1968-1969 and emphasizing those having unsolved problems. /3*

1. Experimental Data

Results Obtained with the Help of the Venera-4 Spacecraft

On board the spacecraft Venera-4 measurements were carried out both during the flight of the spacecraft to the planet and during the smooth descent of the device by parachute in the dense layers of the atmosphere. Upon landing, magnetic, plasma, and ultraviolet measurements were made, During the smooth descent,

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* Numbers in the margin indicate pagination in the foreign text.

which occurred on the nighttime side of the planet near the terminator, the pressure, density, temperature, and composition of the atmosphere were measured.

The fundamental problem of the magnetic measurements consisted of a precise definition of the upper limit of a possible magnetic field of Venus and the determination of the nature of the interaction of the solar wind with the planet. The measurements were carried out with the help of a three-component iron-probe magnetometer. As a result, it was established that the magnetic moment of Venus is 3000 times less than the magnetic moment of the Earth and that Venus exerts a perturbing effect on the interplanetary medium (the nature of the perturbation does not contradict ideas on the formation of a shock wave) [6]. /4

The principal problem of the plasma measurements was the determination of the concentration of charged particles in the ionosphere of Venus. To solve this problem, four charged-particle collectors were mounted on the spacecraft. The flat collectors, suitable for measuring ion concentrations from 50 to 5000 per cm^3 and separating the ionospheric ions from the more energetic particles from beyond the ionosphere, showed that from a distance of around 19,400 km from the surface a significant increase of the ion currents began (which also does not contradict the ideas about the formation of a shock wave by the solar wind in the case of the flow around a planet). The hemispherical collectors, which are useful for measuring concentrations from 10^4 to 10^7 cm^{-3}, did not record any currents at all. The analysis of the currents of the flat collectors recorded at ionospheric altitudes shows that the concentration of positive ions in the nighttime ionosphere does not exceed 10^3 cm^{-3} [4].

The main goal of the ultraviolet measurements consisted of determining the amount of atomic hydrogen and atomic oxygen in the upper atmosphere of Venus. Photon counters were used for this; they record the intensity of the sunlight resonantly scattered by atoms of oxygen and hydrogen (in spectral intervals near 1216 and 1304 Å). No emission was detected in the oxygen lines, which confirms the very small amount of oxygen in the upper atmosphere. The observations in the L_α line of atomic hydrogen permitted establishing the law of variation of its intensity with altitude and estimating the concentration of atomic hydrogen, which at a distance of 10,000 km from the center of the planet amounts to 50 cm^{-3} [33].

The object of the series of measurements carried out during the descent of the spacecraft by parachute consisted of determining the structure of the lower atmosphere of Venus. To achieve this, devices for measuring the composition, pressure, temperature, and density were mounted on the spacecraft along with a radar altimeter, which was supposed to establish a tie-in between the measured data and the surface of the planet.

The chemical composition of the atmosphere was determined [3] with the help of 11 gas analyzers, of which 5 operated when the manometer showed a pressure of 550 mm and the temperature was 25 ± 10°C, and the remaining 6 at a pressure of 1500 mm and a temperature of 90 ± 10°C. Each of the gas analyzers consisted of a hermetic cylinder of specified volume divided in half by a membrane. During operation, the atmospheric gas was introduced into both sides of the membrane, and then the gas analyzer was again pressurized. Carbon dioxide gas was measured by 4 detectors (by 2 in each of the groups), 3 of which were threshold-type and showed greater than 1% and greater than 30%, and one of amplitude-type showed 90 ± 10%. The pressure differences arising upon the /5
absorption of carbon dioxide gas by potassium hydroxide in one of the cells were a directly measured quantity in the two threshold-type and the one amplitude-type detectors, and the difference in thermal conductivities was measured in the fourth detector.

Nitrogen was measured by 2 detectors whose readings established with certainty that its amount is less than 7%. A directly measured quantity was the pressure difference arising in the cells after the absorption of CO_2 and O_2 initially in both and then nitrogen in one of them with the help of zirconium at a temperature of 1000°C. The oxygen content was measured by a threshold detector operating by the combustion of a tungsten thread at 800°C. This detector showed the amount of oxygen to be greater than 0.4%. The amount of water vapor was determined by two threshold detectors measuring the difference of the electrical conductivity arising after the absorption of water vapor by P_2O_5, and by an amplitude detector measuring the pressure difference after the absorption of water vapor in one of the cells by calcium chloride. The results indicate that the amount of water vapor lies within the limits of 0.1-0.7%. One of the detectors, which determines the total amount of O_2 and H_2O from their absorption upon the vaporization of phosphorus, indicated that $O_2 + H_2O < 1.6\%$. Thus, the results of the composition measurements can be summarized in the following relations:

$$CO_2 \approx 90 \pm 10\%, \quad N_2 < 7\%,$$
$$0.4\% < O_2 < 1.5\%, \quad H_2O \approx 1-8 \text{ mg/l}$$

The temperature was measured with the help of two resistance thermometers with measurement ranges of 270-600° K for one and 220-720° K for the other. The mean square error of the measurements for the first detector was ± 4° and for the second, ± 17° [1, 2].

Measurements of the density were carried out with the aid of a densimeter which operated on the principle of the dependence of the ionization current in a gas produced by radioactive material on the density of this gas. Its range of measurements amounted to 5×10^{-4} to 1.5×10^{-2} gm/cm^3, and the mean square error was $\pm 3 \times 10^{-3}$ gm/cm^3 [1]. The pressure was measured by a manometer of the aneroid type with a range of 0.13-7.3 kg/cm^2 and with a mean square measurement error of ± 0.2 kg/cm^2 [2].

The measurements began at 7 hours 40 minutes 52 seconds, Moscow time. /6
The data on the pressure and density were obtained right up to the time of full-scale readings of the devices, which corresponds to 8 hours 30 minutes 31 seconds and 8 hours 50 minutes 00 seconds. The temperature measurements were carried out up to cessation of contact with the spacecraft, i.e., up to 9 hours 13 minutes 51 econds [1]. The tie-in of the measurements with the altitude from the initial point of the measurements was accomplished in two ways. In one, the equation of motion was used for the quasi-steady descent of the spacecraft by parachute, and in the other the hydrostatic equation was used. Both methods of reduction give results which agree with each other within the limits of the measurement errors. The whole altitude range of the measurements amounts to 28 ± 1 km. In this range of altitudes the temperature changes from 300 ± 17° K to 535 ± 17° K, the pressure changes from 0.76 ± 0.2 kg/cm^2 to $17.6^{+0.6}_{-1.3}$ kg/cm^2, and the density changes from $(1.2 \pm 0.4) \times 10^{-3}$ g/cm^3 to $(16.9 \pm 1.2) \times 10^{-3}$ [2]. The height of a uniform atmosphere, H = kT/mg, near the last point of measurement amounts to about 12 km. The temperature gradient throughout the last 10-15 km of the descent is close to the adiabatic value for CO_2.

Results Obtained with the Help of the Mariner-5 Spacecraft

The method of investigating the atmosphere utilized on the Mariner-5 spacecraft consists of determining at various heights the index of refraction of the atmospheric gases in the frequency region 2297 MHz. The quantities directly measured are the traces recorded by stations on the earth of the measurement of frequency, phase, and amplitude of the radio signal transmitted through the different layers in the atmosphere upon the passage of the spacecraft behind the disk of the planet and upon its egress. The reduction of the recorded measurements of the amplitude, frequency, and phase, and then the amount of refraction, was carried out with respect to the center of Venus. For this purpose, accurate trajectory data on the position of the spacecraft relative to the center of Venus and the Earth was used. The exact amounts of refraction at various altitudes were determined from the data on the Doppler frequency shift and the phase caused by the increase in paths (because of the bending) and the variation of the propagation speed of a radio wave in the atmosphere of Venus, which was assumed to be spherically symmetric. The upper part of the refraction profile obtained corresponds to the ionosphere, where the refraction is negative and proportional to the electron density. In the lower atmosphere, the refraction is positive and linear relative to the concentration of each gaseous component. The lowest point of the refraction profile corresponds not to a level near the surface but to the so-called level of critical refraction, i.e., the level below which the radius of refractive curvature of a radio wave is less than the radius of the planet. Near the level of critical refraction the amplitude of the signal dropped below the threshold of detection because of the strong defocusing and weakening of the radio wave. /7

In order to transform from the measured refraction profile to the profiles of concentration, temperature, and pressure in the lower atmosphere, it is necessary to know the composition of the atmosphere.[1] Determination of the total concentration of all molecules for a known composition was carried out with the equation

$$n=\frac{N}{\sum_i x_i n_i}, \qquad (1)$$

1. In this case, use of the Venera-4 data was of great importance.

where

n is the total concentration;

N is the refraction in N-units;

n_i is the volume content of the i-th gas; and

α_i is an empirically determined constant (it is equal to 1.84×10^{-17} for CO_2 and 1.1×10^{-17} for N_2).

The temperature at various levels is found with the help of the hydrostatic equation from the already known concentration profile and from the molecular weight.

The range of altitudes in which the concentration, temperature, and pressure were determined with the help of Mariner-5 started from a point corresponding to a planetocentric distance of 6143 km (where the refractive effect of neutral atmosphere was first detected), and ended at a point corresponding to a distance of 6088 km (where the signal amplitude fell below the threshold of detection); thus, it comprised 55 km.[2] If it is kept in mind that the radius of the hard surface of Venus is close to 6050 km according to a recent estimate of ground-based radar data [10], then the recent data of Mariner-5 refers to an altitude of about 38 km above the surface. The temperature and pressure profiles from the Mariner-5 data are shown by solid curves in Figures 1 and 2 in agreement with [32]. The results of the measurements by Venera-4 are shown in these figures by the dotted line included between the dashed lines which indicate the limits of accuracy of the measurements according to [1]. The heavy dashed lines represent an extrapolation of the profiles using a constant temperature gradient of $8.96°K\ km^{-1}$. The temperature profile from the Mariner-5 data is obtained on the assumption that the atmosphere of Venus consists of 90% CO_2 in agreement with the Venera-4 measurements. It is evident from the figures that the agreement of the temperature and pressure profiles obtained with the help of Venera-4 and Mariner-5 is good. However, a comparison of these profiles with the data on the radius of the hard surface of Venus shows that the recent measurements by Venera-4 do not refer to a level near the surface as was assumed

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2. Thus the range of the values of pressure and temperature obtained is limited.

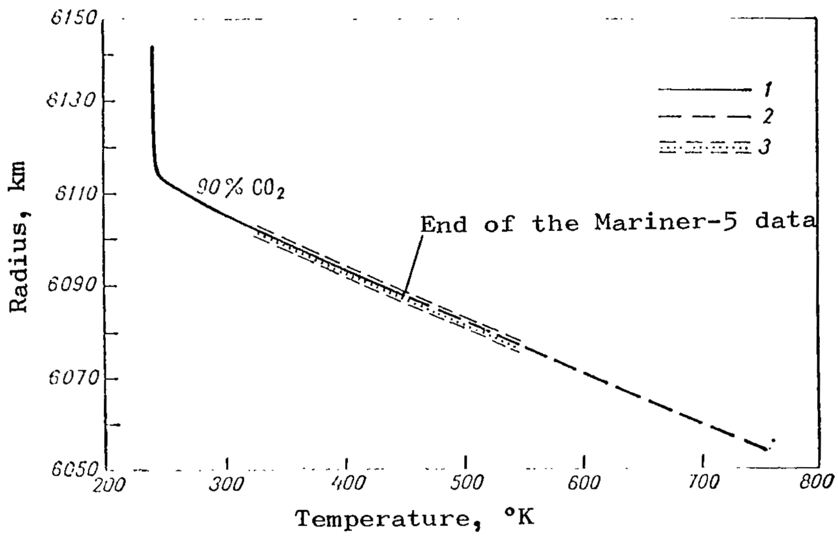

Figure 1. Temperature profiles from the Mariner-5 data (1) and Venera-4 (3). (2) - extrapolated data.

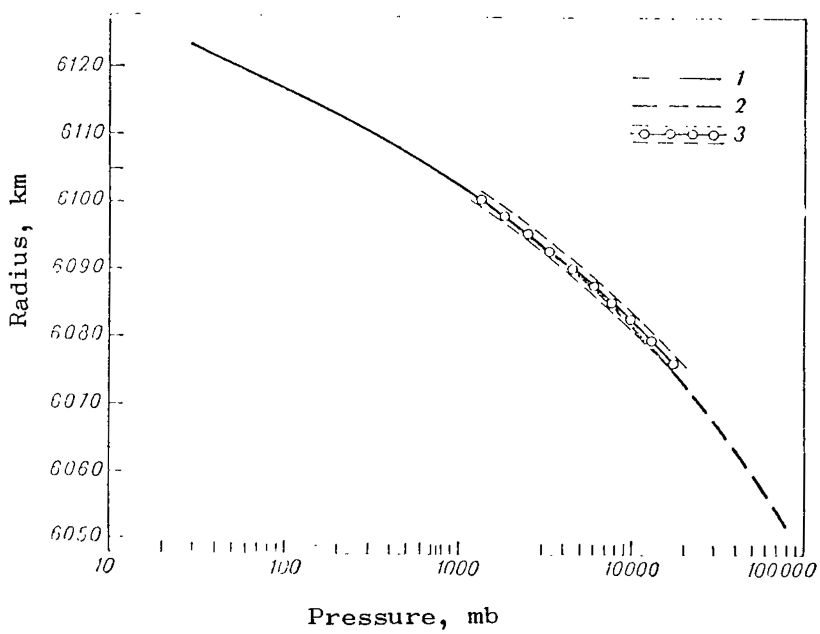

Figure 2. Pressure profiles fromtthe Mariner-5 data (1) and the Venera-4 data (3). (2) - extrapolated data.

initially but rather to a height of 25-30 km above the surface. /9

The upper part of the refraction profile obtained with the help of Mariner-5 was interpreted by means of the equation

$$N = -40.3 \cdot 10^6 \frac{n_e}{f^2}, \tag{2}$$

which determined the dependence of the radio refraction N on the electron concentration n_e (m^{-3}) and the radio frequency f (Hz). The profile of electron concentration thus obtained [31] for the daytime ionosphere of Venus is presented in Figure 3 in the form of a dashed line. Ultraviolet mesurements similar to the measurements by Venera-4 were also carried out by Mariner-5. No emission at all exceeding the background brightness was recorded in the lines of atomic oxygen. The measurements of the radiation scattered by the upper atmosphere of Venus in the Lyman-α line revealed an interesting peculiarity consisting of a variation of the slope of the curve showing the dependence of the intensity of emission on planetocentric distance at a point corresponding to a distance of approximately 9000 km. The results of these measurements are presented in Figure 4 [13]. Possible interpretations of the indicated peculiarity will be discussed below.

Results of Ground-Based Observations

Ground-based methods of investigation have achieved further growth in recent years, among which the spectroscopy of planetary atmospheres has occupied a particularly important place. Belton, Hanse, and Goodey [15] applied a new method to the interpretation of their own spectrophotometric observations of Venus in the range 8000-11000 Å. The method consists of a detailed comparison of the observed spectra with the theoretical, which are calculated for a model of line formation in a uniform semi-infinite nonconservative scattering atmosphere. Because of the fact that the assumptions about the vertical and horizontal uniformity of the atmosphere and the isotropy of the scattering indicatrix which were used in the calculation of the spectra do not correspond to a real atmosphere, the values of the pressure, temperature, and mixing ratio of the gases obtained as a result of the analysis do not correspond to any clearly defined level. They refer to an effective level of formation of the lines situated somewhere below the upper boundary of the clouds. The analysis of the CO_2 bands at 10,500 and 10,380 Å permitted inclusion of the fact that at the

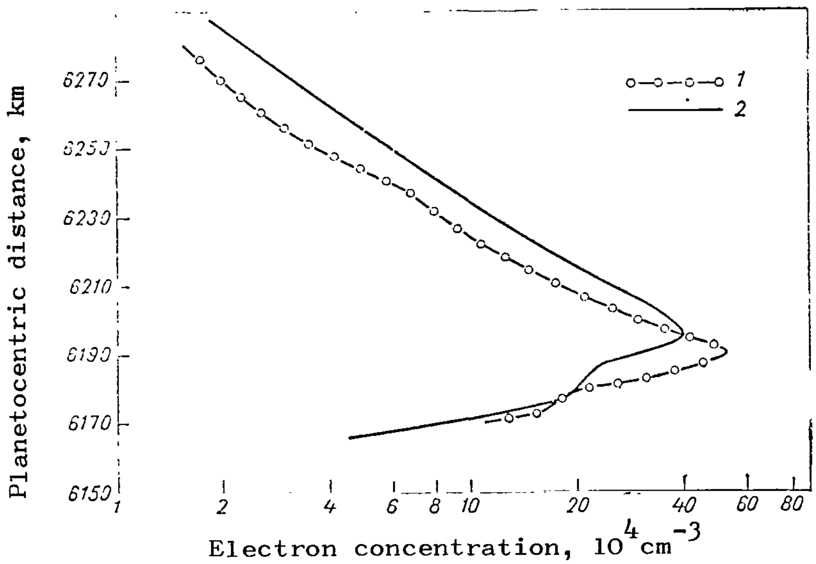

Figure 3. Model of the ionosphere of Venus: (1) Mariner-5 data, (2) calculated data.

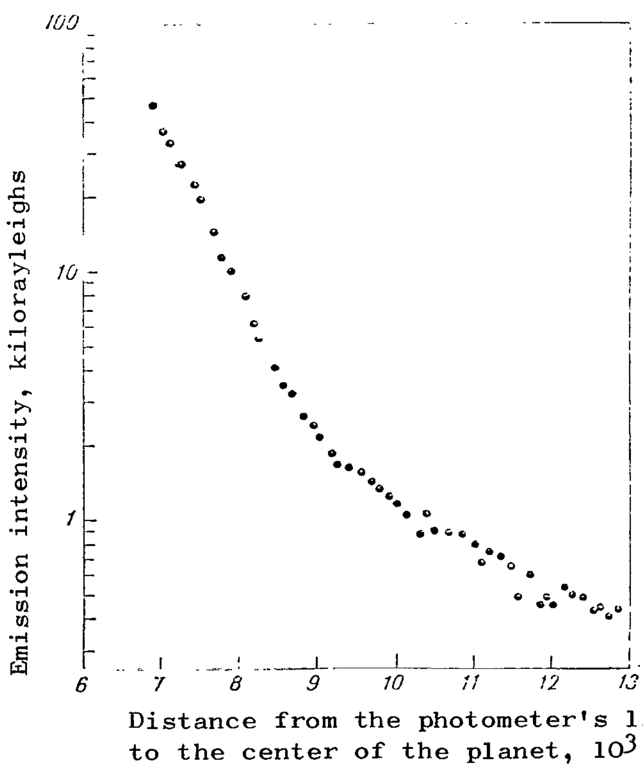

Figure 4. Intensity of the emission in the Lyman-α line recorded by a detector on Mariner-5.

level of formation of these lines the total pressure is around 0.2 atm, and the temperature is 270 ± 25° K. A discussion at hand on the spectrum of the H_2O lines at 8189 Å permitted establishing the fact that it is formed at a level with a pressure of approximately 0.4 atm and that the H_2O mixing ratio is approximately equal to 10^{-4}. The important results of the analysis under discussion /11 also include a conclusion about the range of visibility in a cloud being equal to approximately 4 km and that CO_2 is the primary constituent of the atmosphere.

Recently, the most rapid method interpretation of spectral data using curves of growth has achieved further growth. This consists of the fact that the usual method of curves of growth used in the case of a clear atmosphere lead to significant errors in the determination of the pressure and the amount of absorbing materials in a cloudy atmosphere where multiple scattering plays a significant role. The model of formation of weak lines in a uniform conservative semi-infinite scattering atmosphere developed in 1965 by Chamberlain was extended by Belton [14] for the case of a nonconservative, isotropically scattering atmosphere and for the case of strong lines. Then this new method was applied in an analysis of the spectra obtained earlier by Connes et al. The values obtained for the pressures turned out 2-3 times greater than the effective pressures calculated with the help of the usual curve of growth of Lodenburg-Reiche, which agrees with estimates obtained by means of a comparison of the theoretical and experimental spectra. The cited amounts of the gases HCl, HF, CO, and CO_2 were derived by several others.

Spectroscopic measurements of H_2O and O_2, whose content was measured by Venera-4, are of particular interest. In the papers published recently, [14, 15], the values presented for the H_2O content are significantly lower than was previously communicated - from several microns of precipitable water in a vertical column to 30 to 40 microns. It was also discovered that the H_2O lines are significantly stronger near the equator of Venus than at the poles. It is postulated that noticeable variations may exist in the H_2O content in the atmosphere. The upper limit of the O_2 content was found to be 4×10^{-5} [16]. The lines of carbon monoxide were studied in the paper [19], which were investigated with the help of a Fourier spectrometer. As a result, it was found that the temperature in a cloud in a region of formation of the lines is about 240°K, and the CO content relative to CO_2 amounts to 4.5×10^{-5}.

On the whole, the following parameters best characterize, in Belton's opinion [14], the atmosphere of Venus near the upper boundary of the clouds;

$$P = 0.2 \text{ atm}, \quad T = 240 - 270^\circ \text{K},$$
$$M_{CO_2} = 2 \cdot 10^4, \quad M_{H_2O} = 2, \quad M_{CO} = 2 - 6, \quad M_{HCl} = 2 \cdot 10^{-2},$$
$$M_{HF} = (2 - 6) \cdot 10^{-4}, \quad M_{O_2} = 7 \cdot 10^{-1},$$

where

M is the derived amount of gas in cm-atm per mean free photon path for scattering.

Recently, success has been achieved in the spectroscopy of planets in the region of the vacuum ultraviolet. The spectrum of Venus in the region 1200 to 1800 Å, taken with the help of a rocket spectrometer of low resolution from an altitude of 157 km above the surface of the earth, is described in the paper [39]. /12

Recorded in the Lyman-α line, the signal corresponds to the intensity of the resonantly scattered sunlight in the atmosphere of Venus (of the order of 18 kilorayleighs). A peculiarity has been detected in the spectrum near 1300 Å which is interpreted as proof of the presence of atomic oxygen in the ground state [O (^{3}P)] in the upper atmosphere of Venus. The albedo of Venus in the long wavelength part of the recorded spectral interval was found to be equal to 10^{-3}.

New observations of the dependence of the polarization of the sunlight scattered by Venus on wavelength (using a set of 10 filters in the interval 3400-9900 Å) are described in the paper [18]. The dependences of polarization on phase angle for the period from April 1959 to January 1968 and for phase angles from 7° to 160° are given in this paper. Near the quarter phase the distribution of polarization along the disk of the planet was observed as a function of wavelength.

The results of a large number of photoelectric observations of the phase dependence of the reflectivity of Venus in narrow spectral intervals in the range from 3150 to 10,600 Å were generalized by Irvine [30]. In addition to the phase curves, the dependence of the spherical albedo on wavelength is presented [30]. The radiometric albedo was found to be equal to 0.77 ± 0.07.

New data on the dynamics of clouds were obtained by Dollfus [20] from an analysis of sequential photographs of Venus in the ultraviolet. These data indicate the presence of motions similar to counter-rotation with a period of four days and the fact that the clouds consist preferably not of hard dust but of particles capable of condensing and vaporizing.

Results Obtained with the Help of Venera-5 and Venera-6 Spacecraft [7]

The spacecrafts Venera-5 and Venera-6, similar in construction and equipment, were launched January 5 and 10, 1969 and entered the atmosphere of Venus on May 16 and 17, respectively. The main task of these spacecraft was similar to that which Venera-4 had. Since the Venera-4 spacecraft did not reach the surface, the apparatus released by the Venera-5 and Venera-6 spacecraft were simplified as much as possible and could operate to a pressure of 25-27 atm. The point of entry of the spacecraft into the atmosphere of Venus was located on the nighttime side of the planet at a distance of about 2700 km from the terminator. In connection with the fact that the point of entry of the space- /13
craft was situated further from the terminator and the point of entry of Venera-4 the sharp change in plasma currents associated with the interaction of the solar wind with Venus was expected at the larger distance.

The magnetic and ion measurements confirmed this assumption, having fixed the front of the change in plasma currents at a distance of 3000 km.

The measurements of the scattered ultraviolet radiation again clearly established the presence of a hydrogen corona. The concentration of hydrogen atoms at a distance of 10,000 km from the center was equal to 100 cm^{-3}, i.e., 2 times larger than during the Venera-4 flight.

Devices for measurements of the composition, pressure, temperature, density, and illumination were mounted on the descent apparatus of the Venera-5 and Venera-6 spacecraft. The composition, pressure, and temperature were measured by devices similar to those which were used on Venera-4. A different device was used for the measurement of density; its principle of operation was based on the dependence of the amplitude of the vibrations of a tuning fork on the density of the surrounding medium.

Photoelectric detectors recording radiation in the visible and near-infrared region of the spectrum with a threshold sensitivity of 0.5 watt/m^2 were used for the illumination measurements.

Composition was measured twice by each of the spacecraft: at levels with a pressure of 0.6 and 5 atm and a temperaturesof 25° and 150°C, respectively, by Venera-5 and at levels with a pressure of 1 and 10 atm and a temperature of 60° and 225°C by Venera-6. According to these data, the amount of carbon dioxide gas in the atmosphere of Venus amounts to 93-97%, the amount of nitrogen along with the inert gases amounts to 2-5%, and the amount of water vapor at a level with a pressure of 0.6 atm equals from 4 to 11 mg/l, which is insufficient for saturation at this level.

The range of measurements of the pressure, density, and temperature corresponded approximately to a pressure measurement from 0.5 to 27 atm and a temperature from 25° to 320°C and comprised 36 km for the Venera-5 spacecraft and 38 km for the venera-6 spacecraft. These height ranges of the measurements wee obtained by three methods which are independent of one another: from the hydrostatic equation, from the equation of the descent of the apparatus by parachute, and from the difference in heights established by radar altimeters. All three methods give results which agree with one another. The altitudes recorded by the radar altimeters on the Venera-5 and Venera-6 spacecraft at levels with one and the same pressure and temperature differ from one another, according to the preliminary data, by 12-16 km. It is assumed that this is associated with significant irregularities in the relief of the surface of Venus.

In the case of an adiabatic change in the temperature from the level with /14
a pressure of 27 atm to the level determined by the altimeters, the pressure and temperature near the surface would be 60 atm and 400°C according to the altimeter data of Venera-6 and 140 atm and 530°C according to the Venera-5 altimeter data.

The photoelectric detectors did not record illuminations above the threshold value of 0.5 watts/m^2, with the exception of a single reading of the detector on Venera-5, corresponding to a level of illumination of around 25 watts/m^2; however, it is not clear whether this reading corresponds to an actual phenomenon or whether it is accidental.

Comparison of the Experimental Data

The experimental data obtained recently agree with each other as follows:

1) the atmosphere of Venus consists of more than 90% carbon dioxide gas;

2) the temperature and pressure near the surface reach, evidently, approximately 700° K and 100 atm, respectively;

3) the upper atmosphere of Venus is comparatively poor in atomic oxygen.

Of the experimental disagreements at hand, the most important is the difference in the O_2 and H_2O contents determined from ground-based spectroscopic observations and from the data of the direct measurements by the Venera-4, Venera-5, and Venera-6 spacecraft. The estimate of the amount of O_2 obtained with the help of Venera-4 is larger by two orders of magnitude than the spectroscopic estimate. The data obtained with the help of the later spacecraft give only an upper limit of the content (less than 0.4%), which is somewhat closer to the spectroscopic results; however, the question nevertheless remains open. The results of the measurements of the H_2O content by the three Soviet spacecraft agree with one another, but they presuppose an amount of water vapor larger by an order of magnitude than that which the spectroscopic data indicate. This difference is particularly important from the point of view that the spectral data on H_2O contradict the ice hypothesis of the clouds, and the direct measurements do not. Another sufficiently serious disagreement is associated with the large difference in heights of the isobaric levels, which, according to the altimeter data of the Venera-5 and Venera-6 spacecraft amounts to 12-16 km. The ground-based radar data do not reveal such a large nonuniformity in the relief of the surface of Venus. Because of this disagreement, the question of the average pressure and temperature near the surface remains rather unclear.

The question of the quantitative estimate of the amount of oxygen in the upper atmosphere is also rather unclear because of the contradiction in the results of the measurements of scattered sunlight in the oxygen lines near 1300 Å /15 obtained by the interplanetary spacecraft and on the rocket experiment of Moose, et al. [39]. The results of the rocket measurements confirm a significantly larger thickness of atomic hydrogen than is indicated by the Venera-4 and Mariner-5 data.

2. Results of Theoretical Investigations

Thermal Structure of the Lower Atmosphere

The temperature profiles in the lower atmosphere of Venus have been calculated in many papers applying various methods and assumptions. However, up until this time even the question of whether the greenhouse effect maintains the observed temperatures near the surface remains rather unclear. The difficulties are associated with the lack of information in the first place on the microphysical (concentrations and distributions by size) and the optical (absorption coefficients and scattering indicatrices) characteristics of the Cytherean aerosol, and in the second place about the structure of absorption spectra in the infrared region at high pressures and temperatures. The first is important for accurate calculations of the transfer of solar radiation, and the second is important in an investigation of the probability of filling in the windows of transparency in a thermal spectrum.

For these reasons, the calculations [5, 9, 23] in which high temperatures near the surface were obtained in specific but arbitrarily defined models of the absorbing material of the atmosphere do not answer sufficiently the question of the real mechanisms of transformation of electromagnetic radiation and the role of this radiation in the creation of the observed temperatures of the lower atmosphere of Venus. Samuelson [45] approached this problem differently. He initially tried to determine the optical properties and the vertical structure of the aerosol medium from data on the limb darkening of Venus in the region 8-14 microns, and then he discussed the role which the aerosol medium plays in the creation of the greenhouse effect. The result was that the lower atmosphere has an optical density in the region 8-14 microns equal to 2 and that the carbon dioxide gas was responsible for only 20% to 30% of this amount and the remainder specifies the aerosol. The aerosol medium, for which the albedo for single scattering in the infrared region is significantly less than in the visible region of the spectrum, can produce a large greenhouse effect. However, the calculations of Samuelson [45] showed that a high temperature (725° K) is reached only at the subsolar point at the same time as the average equatorial temperature, is 507° K and the average over the entire planet is only 480° K.

Hansen and Matsushima [25] interestingly arrived at an explanation of the high temperature. They discussed the question of the amount of dust in the atmosphere of Venus, which in the presence of an internal source of heat of the same magnitude as on the earth, could maintain the observed temperatures of the surface. It appeared that for this an aerosol optical thickness of the order of 10^5 is necessary. It is difficult to imagine a physical mechanism which could maintain in a suspended state such an amount of dust in the case of such a small heat flux and, consequently, weakly-developed convection. /16

Theoretical calculations of the temperature profile above the clouds correspond better to the actual levels because of the presence of data on the optical characteristics of this region. Such calculations have been recently carried out in the papers [12, 23, 36].

The paper of Bartko and Hanel [12], although based on outdated data on the composition, contain interesting deductions about the effect of various factors on the temperature profile above the clouds. It was found that the main factors affecting the temperature are the composition and cloud structure. Factors such as the radiative efficiency of the cloud, the reflectivity in the region 1-5 microns, and the level of the pressure played a secondary role. Their deduction about the significant daily variation of temperature above the clouds, which is caused by the absorption of solar radiation near the infrared bands of CO_2, is also an interesting result.

In the paper of Fabian, et al. [23], the daytime and nighttime vertical temperature distributions are computed for various latitudes in the range of pressure variation from a value of 0.0598 mb, assumed at the upper boundary for all latitudes, to an assumed surface. The calculations were carried out by means of numerical integration of the equation of thermal balance over layers (the atmosphere was divided into 40 layers) and over time, from some initial temperature distribution to the achievement of a stable condition. The temperature and pressure profiles obtained as a result for the region below the upper boundary of the clouds scarcely corresponds to reality because of the difficulties indicated above in the assignment of realistic optical characteristics. For the region above the clouds the calculated profiles can be considered as more realistic, which is also indicated by the good agreement with the temperature data of Mariner-5.

The Nature of the Clouds

Information on the nature of the clouds can be obtained from analysis of visual observations, phase curves, polarization, reflection spectra, and infrared limb darkening. Direct measurements of the gaseous constitution of the atmosphere and ground-based spectroscopic measurements of these parameters are the most valuable data. However, it is not clear as of this time what the clouds consist of. And even the question, more widely discussed in the press, as to whether the cloud particles are ice, remains unsettled. /17

Arguments to the effect that the clouds consist of ice particles have been presented in the papers [8, 11, 26, 27, 42]. Obukhov and Golitsyn [8], extrapolating upwards the data of Venera-4, found that the water vapor pressure becomes equal to the saturated vapor pressure over ice in an interval of pressure variation of approximately 150-35 mb and thus the thicknessoof the ice clouds can amount to 7-8 km.

Arking and Potter [11] compared the experimental phase curves of Venus with theoretical ca culations for various models of a cloud. They found that clouds similar to the terrestrial ones, which contain spherical water or ice particles with a radius of about 4 microns, are completely consistent with the phase curves observed in the visible region of the spectrum with the exception of the part of the curve referring to phase angles from 0° to 50°. However, since the observations for these values of phase angle are comparatively rare and of insufficient accuracy, this disagreement cannot be properly resolved until better experimental data is obtained. On the whole, a comparison of the experimental phase curves with various models of the scattering cloud layer permitted the conclusion that the cloud particles are transparent in the visible region of the spectrum and that their index of refraction should have a real part within the limits $1.33 < n < 1.7$ and an imaginary part $k < 10^{-4}$. Such an index of refraction is possessed not only by ice but by many other substances.

Hansen and Cheney [26] carried out theoretical calculations of the reflectivity of ice clouds in the near-infrared region of the spectrum for the purpose of determining the dependence of the absorption pecularities of these clouds on the optical thickness and the sizes of the ice particles. Having compared the calculations with the experimentally observed reflectivity of

Venus, they concluded that the clouds on Venus cannot be optically thick ice clouds. However, optically thin ice clouds ($\tau \approx 5$-10) with a particle radius of 1 micron are consistent with the experimental data within the limits of the observational errors. A later comparison of theoretical calculations with the data of laboratory observations of the reflectivity of ice clouds confirmed this conclusion [27]. But the observed peculiarities in the reflection spectra of Venus can be, generally speaking, associated with a combination of various absorbing and scattering properties of the clouds and the atmosphere above them and therefore positively establishes from the reflection spectra that the clouds are ice, and it does not seem possible that they are made of another substance.

The point of view that ice cannot be the cloud material was expressed in the papers [15, 17, 44]. Belton et al. [15] assume that the spectroscopic data on the pressure, temperature, and amount of water vapor are inconsistent /18 with ice clouds. In order that water vapor be saturated over ice, it is necessary that the pressure be 100 times greater or that the temperature be less by 57° K than those which follow from an analysis of the spectra. Such a discrepancy is difficult to remove by an improvement of the method of observation and the reduction. The assumption that the air above the clouds is significantly drier is useless in the present case, since the H_2O lines are formed within a cloud.

Coffeen [17] carried out a comparison of his own polarization observations with calculations for various scattering mechanisms. It turned out that spherical particles having small absorption in the visible part of the spectrum best satisfy the observations. The real part of their index of refraction is included within the limits 1.43-1.55, and their mean diameter is 2.5 ± 0.5 microns. Such a value of the index of refraction excludes spherical ice particles from the class of possible cloud particles. The totality of data on the spectroscopic upper limits of the content of gases, the thermodynamic possibility of formation of a liquid phase, and the refractive index of the material practically excludes the possibility of the existence on Venus of a liquid cloud. Hard particles of irregular shape can, generally speaking, have a refractive index which exceeds the indicated limits. It is difficult to obtain information about such particles because of the absence of detailed scattering models.

Rea and O'Leary [44] did a semiquantitative analysis of the spectra of Venus in the range $1.4\ \mu < \lambda < 3.4\ \mu$ and showed that the absorption near 1.5 and 2 μ is associated not with the clouds but with CO_2. From this they concluded that in addition to a minimum of the reflectivity near 3 μ, the wide-band absorption peculiarities anticipated for ice in the near-infrared region of the spectrum, particularly at 1.5 and 2 μ, are absent. On the basis of the fact that the intensity of the absorption bands at 1.5 and 2 μ decreases with a decrease in the particle sizes, Rea and O'Leary concluded that either ice crystals are not the main scatterers of infrared radiation or their sizes are less than 1 μ and even less perhaps than 0.1 μ. Since the existence of a large amount of such amount of such particles is improbable from the point of view of the physics of the clouds, the clouds on Venus should not consist of ice. However, as was shown in the papers [27, 42], this conclusion is not sufficiently rigorous. The assumptions were expressed that, besides ice, the clouds can consist of SiO_2, NaCl, C_3O_2, $MgCO_3$, NH_4Cl and others. In this connection, attention should be given to Lewis' result [34], which showed that many volatile materials can be present in the atmosphere of Venus because of the high temper- /19 atures and pressure near the surface. Many of these materials have a refractive index corresponding to the limits which follow from the polarization and phase curve observations. Concerning the physical structure of the clouds, the data at hand agree in that the cloud particles have sizes of the order of several microns and the clouds themselves constitute a rather transparent haze. The limit of visibility evidently exceeds 10 km.

The Upper Atmosphere

One can distinguish five major problems in contemporary investigations connected with the atmosphere of Venus:

1) the composition of the upper atmosphere and the processes controlling it;

2) its thermal structure;

3) the daytime ionosphere and the processes in it;

4) the mechanism of formation of the nighttime ionosphere;

5) the problem of interpretation of the Lyman-α measurements by Mariner-5.

The question of the mechanism of recombination of CO_2 is of central importance in the first problem. Until the measurements by Venera-4 and Mariner-5 it was assumed that CO_2 should dissociate in the atmosphere under the influence of radiation with $\lambda < 1700$ Å and in view of the extremely slow normal recombination due to ternary collisions, its relative amount should decrease rather rapidly with height, and the amount of O and CO should increase. However, the absence of noticeable emission in the lines of atomic oxygen near 1300 Å, which was discovered by the detectors of Venera-4 and Mariner-5, presupposes that the upper atmosphere of Venus is poor in atomic hydrogen and this forces a search for some new CO_2 recombination mechanisms which are more rapid and bimolecular in their nature. It is also necessary to discuss correctly the effect of molecular and turbulent diffusions upon the distribution of CO_2, CO, and O. McElroy [36] concluded, on the basis of the results of Kurt's measurements [33], that diffusion should not play an important role and the recombination of CO_2 occurs in the same place as the photodissociation, by means of the following mechanism, which includes the formation of an intermediate radical CO_3^* :

$$\begin{aligned} CO_2 + h\nu &\rightarrow O(^1D) + CO, \\ O(^1D) + CO_2 &\rightarrow CO_3^*, \\ CO_3^* + CO &\rightarrow 2CO_2. \end{aligned} \quad (3)$$

However, Donahue [21] correctly noted two difficulties in the acceptance of such a scheme. One of them is that with the required rate of flow of the reactions, the lifetime of the unstable radical CO_3^* must be too large (greater than 20 seconds). The other difficulty is associated with failure to take into account the quenching of O (^1D) in collisions with CO_2, which can be significantly more effective than the chemical reaction. The neglect by McElroy of diffusion also seems insuffiently justified. /20

There were also proposed schemes of the recombination of CO_2 which include reactions with hydrogen compounds. The resulting reaction of a recombination in them is

$$CO + OH \rightarrow CO_2 + H. \quad (4)$$

The most fundamental objection to such schemes consists of the fact that they require rates of formation of H atoms equal at least to the rate of photodissociation of CO_2, i.e., 2×10^{11} atoms $cm^{-2}sec^{-1}$. But this is completely inconsistent with the observed concentrations of hydrogen in the upper atmosphere of Venus.

Donahue [21] also proposed the possibility of the existence of a two-stage mechanism consisting of an initial recombination of O into O_2 and (after the transfer of the mixture of CO and O_2 into denser layers) in a final catalytic recombination of CO and O_2 into CO_2. A quantitative analysis of this scheme is difficult since it requires a significant number of data which are lacking at the present time.

The effect of turbulent and molecular diffusion on the neutral and ionized composition of the atmosphere for various initial models and for mechanisms of recombination similar to the terrestrial ones was discussed in the paper [47]. In it, a conclusion was drawn concerning the large effect, by comparison with the earth, of the dynamics of the lower atmosphere on the distribution of the neutral components in the dissociation region. A comparison of the computed electron profiles with those measured by Mariner-5 also led to the conclusion that there exists a deficit of O atoms in the upper atmosphere of Venus.

On the whole, the problem of the composition of the upper atmosphere of Venus remains, to a large extent, indeterminate.

The problem of the thermal structure cannot be correctly posed without knowledge of the composition of the atmosphere. Therefore, all the calculations carried out recently bear a model nature, i.e., they are based on a preliminary assignment of a model for the composition of the atmosphere. The simplest such model is an atmosphere consisting of 100% CO_2. For such a model, McElroy [36] discussed the equation of thermal balance in which he took into account molecular thermal conductivity, part of the ultraviolet and near-infrared solar radiation, the conversion into heat at the site of the absorption, and the intrinsic radiation of the atmosphere. He discussed the heating efficiency associated with photoionization and the heating efficiency associated with photodissociation for calculations of the heating associated with the absorption of solar ultraviolet radiation. The heating efficiency associated with photo- /21
dissociation was investigated separately in the paper [28], where the energy loss rates were calculated in detail for electrons in the case of collisions

with O, O_2, N_2, CO, CO_2, and Ar particles. Then the total heating efficiencies were determined for various wavelengths in the range from 250 to 850 Å. It turned out that they deviated significantly from the value 0.5. In a description of the heating associated with photodissociation, McElroy discussed two cases, one of which assumed that the O (^1D) atom which forms as a result of photodissociation is deactivated at the same place and escapes with only 1.96 eV; the other case assumes that the O (^1D) atom recombines according to the scheme (3) and escapes with 7.4 eV.

The heating due to the absorption of near-infrared solar radiation and the cooling due to the intrinsic radiation were discussed with approximate account taken of the effects of vibrational relaxation.

As a result of the numerical integration of the equation of thermal balance and the hydrostatic equation, McElroy obtained temperature profiles T and concentration profiles n, which are depicted in Figure 5. These profiles correspond to a heating efficiency taking into account photoionization, which is equal on the average to 0.5, and the case where O (^1D) is not deactivated but recombines with the escape of 7.4 eV. It was also shown that if O (^1D) is deactivated and escapes with only 1.96 eV of heat, then the temperature of the exosphere will be approximately 30° lower.

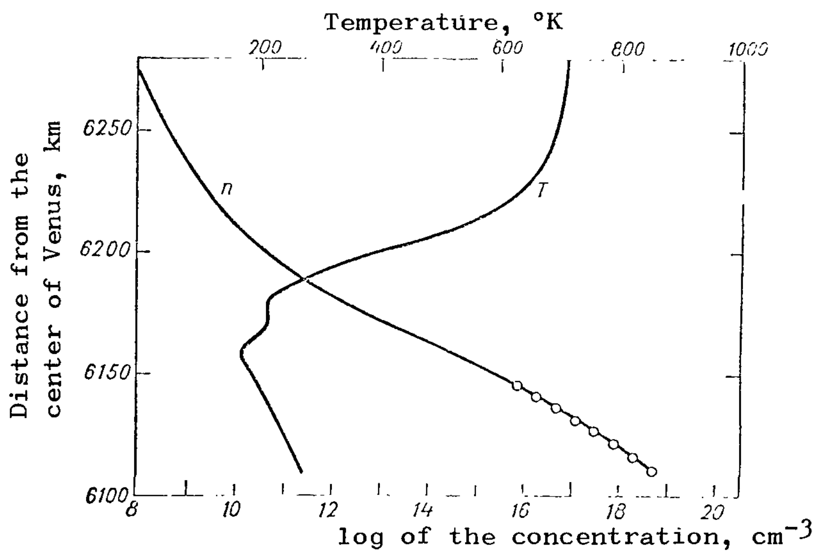

Figure 5. Model of the neutral upper atmosphere of Venus.

The heading efficiency, to which the temperature profiles in the thermosphere are most sensitive, was also determined in the paper [48] by means of empirical selection. On the basis of the selection, the fact that the rate of decrease of the electron density in the upper part of the ionosphere is sensitive to the value of the heating efficiency, was established. Constructing models of a neutral atmosphere and electron profiles for various heating efficienc es, they selected the one out of all of these which gives the best agreement of the experimental and theoretical electron concentration profiles. Thus, the heating efficiency for Venus was found to be equal to 0.35 ± 0.1. In the paper [29], the temperatures of Venus' exosphere were calculated for various heating efficiencies and by a method somewhat different from the one which McElroy used. For efficiencies of 0.19 and 0.35, temperatures were found equal to 577° and 718°K, respectively, which differ significantly from the results of McElroy if it is taken into account that the latter used a significantly larger efficiency. /22

On the whole, it is not possible to assume that the available computed temperature profiles are sufficiently close to the temperatures actually existing in the upper atmosphere of Venus. Nevertheless, in the absence of detailed data it is possible to use them as a first approximation.

Concerning the structure of the daytime ionosphere of Venus, its main peculiarities recorded by Mariner-5 are well explained if it is assumed that the ionosphere represents a layer of type F_1 with CO_2^+, the main ion. On the basis of .the reaction scheme

$$\begin{aligned} CO_2 + h\nu &\rightarrow CO_2^+ + e, \\ CO_2^+ + e &\rightarrow CO + O \end{aligned} \tag{5}$$

with the dissociative recombination rate constant equal to $3.8 \times 10^{-7} cm^3 sec^{-1}$, McElroy [35] constructed a profile of the electron concentration (see Figure 3, curve 2). This profile differs from the observed one (curve 1) by less than 30%. Such good agreement for Venus raises the question of whether an ionosphere of type F_1 applies for Mars, for which the same composition is assumed.

The explanation of the nighttime ionosphere recorded by Mariner-5 is a significantly more complicated task. The run of the measured electron concentration, which has a maximum of the order of $10^4 cm^{-3}$ at a distance of

6400 km and to 10^2 at 7500 km, indicates that the scale height of the electron profile above 6500 km comprises a quantity of the order of several hundreds of kilometers. Such a large scale height should be associated with the presence of light ions such as He^+ and H_2^+. McElroy and Strobel [38] discussed various possible sources of ions in the nighttime atmosphere and concluded that the transfer of He^+ and H_2^+ ions from the daytime side of the planet at large altitudes and their subsequent diffusion below is most probable. Thus, above a certain level z_0 the ionosphere is in ambipolar-diffusive equilibrium, and lower down He^+ and H_2^+ will enter into a reaction with CO_2, N_2, H_2 and others, and as a result of the corresponding altitude variation of the rate of recombination and diffusion a maximum of heavy ions is formed. However, it remains unclear whether the rate of ionization of hydrogen and helium on the daytime side is sufficient to provide the necessary flux of these ions to the nighttime side and compensate in the long run the total rate of loss of ions in the entire thickness of the nighttime ionosphere. /23

Of all the problems connected with the upper atmosphere of Venus, the problem of the interpretation of the ultraviolet measurements of Mariner-5 is the most widely discussed in print at the present time. The question consists of explaining the variation in the slope of the dependence of the intensity of scattered L_α radiation on planetocentric radius observed at a distance of 9000 km from the center of the planet. These data can conform to the barometric formula only if the relationship of mass to temperature above and below 9000 km differs by a factor of two, with the heavy or cold gaseous component predominating below 9000 km and the light or hot component dominating above. To explain this effect, four models were assumed: 1) two-temperature, 2) deuterium, 3) a model of molecular hydrogen and 4) an asymmetric model. These models were discussed in detail in the papers [10, 21, 22, 37, 49]. The first model does not merit serious attention. The model of molecular hydrogen, in which L_α is produced by photodissociation of H_2, was defended by Barth [13]. However, Donahue [21] presented several serious objections to this model. One of them consists of the fact that at those concentrations of H_2 which are required to explain the observed intensities of Lyman-α in the interval from 6500 to 9000 km, the rate of production of H atoms due to photodissociation of H_2 and the reaction $H_2 + O\ (^1D) \rightarrow H + OH$ is so great that it is not compensated by diffusion and the escape of H from this region. The other objection is associated with difficulties in explaining the observed electron profile in an atmosphere rich in H_2. In such an atmosphere, the ionospheric layer should be significantly higher and significantly more spread out.

The papers [22, 37] are devoted to an analysis of the deuterium model. In /24 this model, H atoms produce the L_α line above 9000 km, and the D atoms produce it below 9000 km. The line of heavy hydrogen is shifted relative to the L_α line of light hydrogen by only 0.33 Å in all, and the D atoms scatter solar radiation almost the same as H atoms. To explain the observed intensities, it is necessary to assume that the ratio of the concentration of deuterium to the concentration of hydrogen at a distance of 6500 km from the center of the planet is 10:1. As shown in the paper [37], a transition across the thermosphere can increase the ratio n (D)/n(H) by only 100 times, and therefore the ratio n (D)/ n (H) in the lower atmosphere should be 0.1, which contradicts finally the terrestrial experiment. However, in the atmosphere of Venus, isotopic fractionation with escape could occur significantly more intensively than on the earth and the relative amount of deuterium compounds could significantly increase. Some possible methods for an experimental check of this proposal are discussed in the paper [37]. The most serious objection to this hypothesis is associated for the present with the fact that the infrared spectra of HCl in the atmosphere of Venus does not reveal the presence of DCl lines.

The role of asymmetry of the atmosphere in the creation of the observed effect was discussed in the paper [49]. It is shown there that in an atmosphere consisting of only H, the effect will be observed if the temperature at the antisolar point of the exosphere is 2-3 times larger than at the subsolar point. The presence of such an asymmetry is, of course, only slightly probable. In an atmosphere consisting of D and H, an asymmetry is also required to explain the data of the observations. The concentration of deuterium at a critical level of constant temperature should drop by a factor of 10 from the subsolar point to the antisolar point. It should also be noted that for complete assurance that the effect discovered by Mariner-5 is connected not with a random phenomenon but with one constantly present in the atmosphere, repeated measurements are necessary.

The Lack of Water on Venus

A comparison of the total amount of various gases comprising the atmosphere of Venus with the amount of volatile substances contained in the atmosphere, hydrosphere, and core of the earth reveals that on Venus there is at least 10^4 times less water than on the earth. If one assumes that the atmospheres have an identical origin, then since the masses and diameters of Venus and the earth are almost identical, the amounts of gases released as a result of degassing should also be approximately the same. Therefore, it is possible to assume that the difference in the composition of the two planets is associated with their different distances from the sun, the different initial thermal structures of the atmosphere, and the different subsequent evolution. The /25 papers [24, 43, 46] are devoted to an analysis of these questions. In them, the lack of water on Venus is explained by the more rapid processes of photodissociation of H_2O and dissipation of H than on the earth. If one assumes that Venus lost in 4.5×10^9 years as much water as was contained on the earth, then in the course of this period of time the rate of photodissociation of H_2O and the escaping flux of hydrogen should have had a magnitude of the order of 10^{11} atoms $cm^{-2}sec^{-1}$. On the earth, the rate of dissociation of H_2O is only 10^8 atoms $cm^{-2}sec^{-1}$. However, on the earth, oxygen on the one hand shields a large part of the H_2O from dissociation, and on the other hand a "cold trap" - the tropopause with a temperature in the equatorial region of around 190°K - does not allow a large amount of water vapor to ascend into the stratosphere. Since there is significantly less oxygen on Venus and the temperature of the tropopause is higher (around 240°K according to the Mariner-5 data), the photodissociation of H_2O will proceed in the first place with a larger coefficient, and in the second place at levels where the concentration of H_2O is significantly greater. Therefore, it is completely probable that the rate of photodissociation on Venus reached of the order of 10^{11}-10^{12} atoms $cm^{-2}sec^{-1}$. The released hydrogen diffused upward, was ionized, and carried away by the solar wind, but the oxygen was used in reactions converting CH and CO into CO_2.

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